Volatile and semi-volatile organic compounds in smoke exposure of firefighters during prescribed burning in the Mediterranean region

VOLATILE AND SEMI-VOLATILE ORGANIC COMPOUNDS IN SMOKE EXPOSURE OF FIREFIGHTERS DURING PRESCRIBED BURNING IN THE MEDITERRANEAN REGION

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Abstract

Prescribed fires can be used as a forest management tool to reduce the severity of wildfires. Thus, over prolonged and repeated periods, firefighters are exposed to toxic air contaminants. This work consisted in collecting and analysing smoke released by typical Mediterranean vegetation during prescribed burning. Sampling was performed at five active zones on the island of Corsica. Seventy-nine compounds were identified: volatile organic compounds and semivolatile organic compounds, including polycyclic aromatic hydrocarbons. Depending on exposure levels, the toxins present in smoke may cause short-term or long-term damage to firefighters' health. The dangerous compounds emitted, benzene, toluene, ethylbenzene and xylenes, were quantified. Their concentrations varied as a function of the study site. These variations were due to the intrinsic and extrinsic characteristics of the fire site (e.g. plant species, fire intensity and wind). Our results show that benzene concentration is high during prescribed burning, close to the exposure limit value or short-term exposure limit. Benzene can be considered as a toxicity tracer for prescribed burning because its concentration was above the exposure limit value at all the study sites. The authors suggest that respirators should be used to protect staff during prescribed burning operations.

Additional keywords: air quality, BTEXs, firefighter exposure, forest fire smoke, SVOC, VOC.

Introduction

Every year, thousands of hectares of forest are destroyed by wildfires in the Mediterranean basin. In France, 4 million hectares of scrubland and 1 million hectares of pine forest are affected by fire during the summer. To prevent wildfires, prescribed burning is used as a forest management tool (Rigolot 2003; Fernandes and Botelho 2004). Prescribed burning: (i) reduces fuel load and fire risks; (ii) recreates natural disturbance dynamics; and (iii) restores the ecosystem (Weber and Taylor 1992; Graham et al. 2004; Fernandes and Rigolot 2007). During prescribed burning operations, personnel are repeatedly exposed to smoke and volatile organic compound (VOC) emissions for prolonged periods. In France, operating staff have no respiratory protection, so there is a real health risk (Reinhardt and Ottmar 2004; Stefanidou and Athanaselis 2004), because pollutants and particulate matter can penetrate the upper respiratory tract, and then down into the lungs. Smoke is considered as one of the damaging effects of prescribed burning. Many studies have been carried out on the

analysis of smoke during forest fires and prescribed burning in theUSA (Kelly 1992; Reinhardt et al. 2000), Greece (Statheropoulos and Karma 2007), SE Asia (Muraleedharan et al. 2000), Australia (Reisen et al. 2006; Reisen and Brown 2009) and Russia (Lee et al. 2005). Determining the composition of smoke is complicated by the numerous compounds emitted from the external environment (e.g. plastics, fertilisers, pesticides), leading to secondary compounds (Statheropoulos and Karma 2007). The reaction of partial combustion releases a large number of molecular pollutants and particulates (Wade and Ward 1973;Ward 1989; Brown and Bradshaw 1994; Korontzi et al. 2003; Miranda et al. 2005; Statheropoulos and Karma 2007; Wise 2008). The compounds emitted in smoke have an impact on air quality and human health. Smoke consists of permanent gases, VOCs, semi-volatile organic compounds (SVOCs) and particulates. The permanent gases in the smoke from forest fires are CO, which is the major toxic component, CO_2 and NOx ($NO+NO_2$) (Muraleedharan et al. 2000). The VOCs emitted include ethane (Ward 1989; Miranda 2004) and aldehydes (Schauer et al. 2001; Reinhardt and Ottmar 2004; Statheropoulos and Karma 2007), together with benzene, toluene, ethylbenzene and xylene (Reh and Deitchman 1992; Hoerning et al. 1996; Friedli et al. 2001; Statheropoulos and Karma 2007), and the SVOCs include polycyclic aromatic hydrocarbons (PAHs; Kelly 1992; Muraleedharan et al. 2000) and organic acids (Ward 1989; Dost 1991). Exposure to high levels of carbon monoxide (CO), respirable particulates, aldehydes, VOCs and SVOCs can cause short-term adverse health effects to firefighters, such as coughing, eye irritation, shortness of breath, headaches, dizziness and nausea (Dost 1991; Reisen and Brown 2009).

No epidemiological studies have been carried out on the firefighters involved. However, epidemiological studies of indoor and community exposure to biomass smoke indicate a consistent relationship between exposure and increased symptoms of respiratory troubles, increased risk of respiratory illness and decreased lung function (Johnson et al. 2002; Chen et al. 2006). The health effects of long-term exposure to smoke from forest fires can include nose and eye irritation, acute respiratory infections and lung function problems (Malilay 1999; Reinhardt et al. 2000). Short-term exposure has been associated with lung function decrease and increases in the airway sensitivity of firefighters (Fowler 2003; Slaughter et al. 2004). Bushfires and prescribed burning episodically expose humans to high levels of smoke pollutants for short periods of time (Morawska and Zhang 2002). Concentrations exceeding exposure limit values of PM10 (particulate matter 10 mm in size) (Reh and Deitchman 1992; Mott et al. 2005), PM2.5 (particulate matter 2.5 mm in size) (Statheropoulos and Karma 2007), CO and formaldehyde (Reinhardt et al. 2000) have been reported. The VOCs determined were the products of several metabolic pathways (endogenous compounds) on inhaled contaminants (exogenous compounds). Fires are known to produce a variety of these compounds, but little characterisation work has been done. If inhaled, benzene causes headaches, dizziness, nausea, confusion and respiratory tract irritation. In the long term, it is a human carcinogen (Margossian 2002). Long-term exposure to toluene can cause organic psychosyndromes and cardiomyopathy. No detrimental effects of metabolites due to ethylbenzene have been reported in humans. Xylenes can cause vomiting and a risk of pulmonary oedema in the short term (Margossian 2002). The possible synergistic effects of exposure to a mixture of toxic substances in forest fire smoke are unknown. To our knowledge, no study has been carried out on the toxicity of smoke from the prescribed burning of typical Mediterranean vegetation in Europe.

The type and the concentration of compounds emitted into the atmosphere

from burning plants depend on the type of fuel, fireline intensity, fuel moisture, meteorology and geographical location (Miranda et al. 2005, 2007). The forest-firefighting community has expressed its concern about the health risks due to short- or long-term exposure to this smoke.

The general aim of the present work is to contribute to the identification of this source of atmospheric pollution, obtain data regarding smoke emissions in Mediterranean forests and inform firefighters of the risks faced owing to smoke inhalation.

This specific aims of this study are: (i) to identify the VOCs and SVOCs emitted during prescribed burning in order to evaluate the impact of smoke on the firefighters; (ii) to quantify the BTEXs and (iii) to compare the benzene, toluene, ethylbenzene and xylenes (BTEX) toxicity with the short-term exposure limit (STEL) and measure the health risks for firefighters, at five sites in Corsica with typical Mediterranean vegetation. The next section presents the materials and methods used for the present work, followed by a presentation of the results with a discussion of the health risks encountered by prescribed burning operating personnel.

Materials and methods

Experimental plots and sampling

The sampling was conducted on the island of Corsica (France–western Mediterranean, Fig. 1) at five different sites. Table 1 lists the sites and their characteristics. The sites were selected by the ONF (Office National des Forêts) and forest-fire prevention operating staff. Sampling was performed by the same operating personnel who performed the prescribed burning at the five sites. VOC and SVOC emissions were measured on mixed samples (i.e. without distinguishing between the flaming and smouldering phases). The distance between the sampling area and the fire front was between 1 and 10 m, corresponding to the position of the operating staff. The staff consisted of four persons who controlled the fire by means of flaming torches. Each person was equipped with a portable sampling pump. The operating staff performed the sampling with Tenax TA® tubes (Supelco®, Saint-Quentin Fallavier, France) at three different times during the prescribed burn, in order to provide triplicate measurements. Sampling was carried out for a period of 15 min at a flow-rate of 150 mL min^{-1}. Twelve samples were collected at each site and analysed. In total, 60 samples were studied. The Tenax TA sorbent tubes used were multibed glass tubes, with the dimensions 11.5 x 6 mm outer diameter (o.d.) x 4 mm inner diameter (i.d.), in order to capture low - and medium - volatility organic compounds. The sorbent tubes were transferred to a freezing box in the laboratory and analysed the next day using automatic thermal desorption–gas chromatography–mass spectrometry (ATD-GC/MS). It should be noted that sorbent tubes have previously been used in other studies for sampling VOCs and SVOCs (Reinhardt et al. 2000; Reisen et al. 2006) before GC analysis.

Exposure limit

All over the world, national health and safety commissions or agencies set concentrations of substances in the air at or below which exposure is considered to be acceptable. In the USA, the National Institute for Occupational Safety and Health (NIOSH) advises the Occupational Safety and Health Administration (OSHA) on health hazards in the workplace and establishes recommended exposure limits that are based on thorough reviews of available scientific information. In France, CIRC

(Centre International de la Recherche sur le Cancer) and other agencies (Institut National de la Recherche et de la Santé, Agence Française de Sécurité Sanitaire de l'Environnement et du Travail) publish lists of carcinogenic substances or those suspected of being so. An important parameter is the STEL, a maximal concentration to which workers can be continuously exposed for up to 15 min without adverse effect. In the present work, different products involved in burning biomass were identified and quantified and their values are compared with the STEL.

ATD-GC/MS analysis of VOCs

The analyses were carried out 1 day after each experiment in the laboratory using an automatic thermal desorber Perkin Elmer_ ATD Turbomatrix. For the thermal desorption of VOCs, helium (He) flow was set at 30 mL min^{-1} with a column head pressure at 3626 x 10^{-6} Pa (25 psi). The sorbent tube was brought to 280ºC over 10 min and a carrier gas flushed the sample towards a cold trap at 5ºC. In a second step, the cold trap (22 cm, 0.53mm i.d.; Supelco) was programmed to increase temperature from 5 to 280ºC at 40ºC s^{-1}, then held isothermally at 280ºC for 3 min. The compounds were then desorbed onto the chromatograph under helium as carrier via a heated transfer line maintained at 280ºC. The injector temperature was set to 2808ºC. The ionization energy for mass detection was set to 70 eV and electron ionisation mass spectra were acquired over the mass range 35–350 Da. The chromatograph and the mass spectrometer were Perkin Elmer Clarus 500® apparatus (Waltham, MA, USA). The chromatograph was equipped with a non-polar column (Rtx®-1 fused silica column, dimethylsiloxane, Resteck, Lisses, France), length 60 m and i.d. 0.22 μm. This column was coupled with the mass detector. Detection was carried out by a quadripolar analyser made up of an assembly of four parallel electrodes of cylindrical section. The oven temperature of the chromatographwas programmed from 50 to 260ºC at 2ºC min^{-1} and then held isothermally at 260ºC for 10 min.

Identification and quantification

The methodology used to identify individual components was based on the comparison of their GC retention indices (RI) on non-polar and polar columns with those of authentic compounds or literature data (König et al. 2001; NIST WebBook, see http:// webbook.nist.gov/chemistry, accessed 2006). The RIs on nonpolar and polar columns were determined relative to the retention time of a series of n-alkanes with linear interpolation (van Den Dool and Kratz 1963). The results were computer-matched with commercial mass spectrum libraries (Adams 2001; König et al. 2001; http://webbook.nist.gov/chemistry) and spectra were compared with those in our own library of authentic compounds.

The majority of these compounds were commercial standard components. The relative amounts of the individual components were calculated on the basis of their GC peak areas, obtained on a capillary Rtx-1 column, without flame ionisation detector (FID) response factor correction.

Quantification was performed for benzene, toluene, ethylbenzene and xylenes (o-xylene,m-xylene and p-xylene). The method of external calibration was used with a commercial mixture of BTEX in methanol from Restek® (Lisses, France) in the range 5–250 mg mL^{-1}. Triplicate injections of standards were made each set of concentrations for the curves of external calibration standards. The correlation coefficient (R^2) for the linear regression of the curves of external calibration standards varied between 0.996 and 0.999, indicating a good correlation between the detector's

response and the concentration of injected products.

Statistical analysis

Analyses of variance (ANOVA test) were used when the conditions of application were satisfied (variance homogeneity and normality of the populations). Pearson's test was carried out to find correlations between BTEXs concentrations and many parameters such as abiotic factors and fire data. The Statgraphics for Windows program of Statistical Graphics Corporation_ (Waltham, MA, USA) was used for this test.

Results and discussion

Identification of VOCs during prescribed burning

ATD-GC/MS analysis of the five prescribed burning sites led to the identification of 79 compounds (Table 2), including benzene and benzene derivatives, phenol and phenol derivatives, organic acids, terpenic compounds, alkanes, alkenes and aldehyde compounds. Other ring systems included furans, 1H-indene, pyrroles, and naphthalene and their derivatives. These compounds were reported at sites A–E (Table 2). Many other compounds (VOCs and SVOCs) could not be identified because their mass spectra or retention indices were not included in our databank or in commercial databanks. Among the 79 individual compounds, 65 were identified by comparing their electronimpact (EI) mass spectra and retention indices with those of our own library. Compounds 12, 16, 27, 36, 38, 45, 47, 49, 63, 65, 66, 68, 69 and 71 were identified by comparing their EI-mass spectra and retention indices with those of commercial libraries or literature data (Ward 1989; Reinhardt et al. 2000; Andreae and Merlet 2001; Reisen et al. 2006; Statheropoulos and Karma 2007). The same compounds (reported in Table 2) had previously been found in forest fires (Ward 1989; Andreae and Merlet 2001; Statheropoulos and Karma 2007) and prescribed burning operations (Reinhardt et al. 2000; Reisen et al. 2006). The smoke composition (VOCs and SVOCs) was approximately the same at the five sampling sites and in the literature. Indeed, many studies (Austin et al. 2001; Austin and Wang 2002) show that the composition of the smoke produced by fires of various kinds is similar.

Only at site E were five monoterpenes (33, 44, 46, 54 and 64; Table 2) and five sesquiterpenes (75–79; Table 2) observed. This burning operation was conducted under *Pinus laricio*. The needles of this species emit these compounds by vapour-transpiration (biogenic volatile organic compounds; Rezzi et al. 2001).

Quantification of BTEX during prescribed burning

The concentrations of BTEX identified for all sites are given in Table 3. Total BTEX concentrations varied significantly between the different sites (ANOVA, $P < 0.05$). Benzene concentrations were not statistically different at sites A and B (ANOVA, $P < 0.05$). Toluene concentrations differed significantly between sites A and E, B and D, and site C (ANOVA, $P < 0.05$). There is a statistically significant difference between sites A, C and E regarding ethylbenzene concentrations, and between all the sites regarding xylene concentrations (ANOVA, $P < 0.05$).

The highest benzene concentrations were found at sites C (54 mg m^{-3}) and D (40 mg m^{-3}). The benzene levels at sites A, B, C and D were above the exposure limit value (ELV) and STEL (benzene: ELV, 30 mg m^{-3}; STEL, 16 mg m^{-3}). For sites A

and B, the benzene levels were close to this limit value. The highest BTEX contents were measured at sites C and D, but their concentrations were much lower than the ELV. These higher concentrations can be explained by the high fuel load and the proportion of cellulose. The vegetation was dense at both sites (Table 1), resulting in much less complete combustion. The vegetation density of sites A, B and E was lower, resulting in lower BTEX concentrations. The correlation test between data plots (Table 1) and quantities of BTEX showed no correlation.

In comparison with literature data (Reinhardt et al. 2000; Reisen et al. 2006; Statheropoulos and Karma 2007), we found that BTEX concentrations were a 1000 times higher a few metres from prescribed burning operations than near forest fires. This can be explained by the distance between the sampling position and the flame front, which was between 1 and 10 m. In forest-fire studies, that distance is between 70 and 150m (Statheropoulos and Karma 2007).

In the present study, prescribed burning was carried out on different vegetation types, with a wide variety of parameters such as meteorological factors (pre-ignition temperature, fuel moisture hydrometry, wind, etc.), plant species, fuel load and fire intensity. All these parameters can influence the quantitative concentrations of BTEXs. Dokas et al. (2007) explain that the concentration of smoke from forest fires depends on meteorological data such as wind speed and direction, temperature and relative humidity. Ward (1989) show that PAH emissions increase with vegetation density. Faix et al. (1991) studied the relationship between the degradation of cellulose and the production of benzene derivatives. Low-diameter fuel loads burn almost completely at the combustion stage, which is not the case with broader-diameter fuels. Alén et al. (1996) show that the proportion of different compounds varies with degradation temperature. Butt (2006) explains that the concentration of phenols increases with oxygen concentration.

All these changes may be responsible for the variation in BTEXs between the study sites. The Pearson test was performed to investigate the correlation between the concentrations of BTEXs and the various parameters. No particular predominant factor was identified with regard to the variations in these compounds. The fire intensity of prescribed burning is considerably lower than that of a forest fire, resulting in a slower combustion and more often incomplete combustion process.

Health risks

Table 3 shows that the concentration of total BTEX was well above the ELV at sites A–D. It was only below the ELV at site E. Concentrations of benzene, which is considered a potential carcinogen, exceeded STEL (and ELV) limits at all the sites. Exposure to benzene at 160 mg m^{-3} (for 60 min) leads to symptoms of illness, and exposure to between 16 and 50 mg m^{-3} (for 5 hours) results in headaches, lassitude and weakness (Statheropoulos and Karma 2007). In our experiments, benzene concentrations were between 12 and 54 mg m^{-3}, implying shortterm intoxication.

Timothy et al. (2000) established toxic potential P(t) by summing the concentrations of different toxic compounds. Applying this P(t) to TEX (toluene, ethylbenzene and xylenes) levels at all the study sites gave a toxic potential of TEXs less than 1. TEXs are molecules with relatively low toxicity and high ELVs. In the literature, the concentrations of VOCs measured were not greater than limit values (Reinhardt et al. 2000; Miranda et al. 2005; Reisen et al. 2006; Statheropoulos and Karma 2007).

There are other compounds of importance with regard to human health risk. Phenolic compounds (phenol and derivatives identified in the smoke from the sites;

Table 2) are important because they are serious irritants, produced in abundance by the partial oxidation of cellulose fuels. Naphthalene (59) and naphthalene derivatives (67, 70) are carcinogens. Some aldehydes are extremely irritating to humanmucous membranes (12, 24, 32, 34, 45 and 61).

The long-term health effects have not been studied, making it difficult to correlate exposure to toxic smoke with inherent risks. On the basis of our results, the authors suggest the use of respirators to protect staff involved in prescribed burning operations.

Conclusions

The present work consisted in the chemical analysis of the smoke released by prescribed burning operations in Corsica. ATD-GC/MS analysis of smoke from burning biomass led to the identification of 79 compounds. These compounds were derived from the distillation and decomposition of biopolymers. Some of them are toxic or harmful to humans, such as BTEXs. Although the toxicity of the smoke from prescribed burning was not clearly established, we showed that there was a potential risk for the health of firefighters. Benzene concentrations were close to the ELV or STEL, implying that this compound can be considered as a tracer of toxicity for prescribed burning.

At the international scale, the wearing of a respirator is not compulsory. In France, firefighters are only protected from exposure to large particles by wearing a hood. As a precaution, the authors consider that firefighters involved in prescribed burning operations should wear a protective respirator, which would keep out fine particles and decrease the quantities of dangerous compounds inhaled.

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Table 1. Main characteristics of the study sites and main parameters concerning prescribed fire

	Site A	Site B	Site C	Site D	Site E
Locality	Sainte Lucie de Porto-Vecchio	Cuttoli	Corte	Quenza	Ospédale
Coordinates	41°42′N	41°59′N	42°18′N	41°46′N	41°41′N
	09°20′E	08°54′E	09°09′E	09°08′E	09°12′E
Elevation (m)	0	650	400	805	950
Main species	*Quercus ilex* L., *Olea europaea* L., *Arbutus unedo* L., *Cistus monspelliensis* L., *Cytisus triflorus* L., *Erica arborea* L.	*Arbutus unedo* L., *Erica arborea* L., *Cistus monspelliensis* L.	Leaf of *Quercus ilex* L.	*Juniperus nana* L.	Scrub burning under *Pinus laricio*
Date of prescribed fire	12 July 2004	10 June 2005	14 June 2005	16 June 2005	10 April 2007
Slope (%)	0–30	0–10	0	0–20	5–10
Vegetation height (cm)	80–250	80–150	1–10	10–20	20–35
Fuel load ($g\ m^{-2}$)	1160	1200	1370	1450	960
Vegetation cover (%)	50–60	50–60	60–70	70–80	30–40
Burning area (ha)	0.06	2	0.4	2	1
Relative humidity, RH (%)	20–23	22–25	24–25	30–35	21–23
Temperature (°C)	30–32	22–24	22–25	14–16	24–26
Wind velocity ($km\ h^{-1}$)	40	20	<5	<5	<5

Table 2. Volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) identified during prescribed fires

Compounds are listed in order of elution from the apolar (Rtx-1) column. Compounds listed were present at 80% to the five sites (A–E) and collected in 12 samples. RIl, literature retention indices on the apolar column (Jennings and Shibamoto 1980; Joulain and König 1998; NIST WebBook, see http://webbook.nist.gov/chemistry, accessed 2006). RIa, retention indices on the apolar Rtx-1 column. A correct isomer was not identified for data marked with an asterisk (*). N, the total number of samples for the all sites. Superscript letters represent the sites sampled

N	Compounds ($n = 60$)	RIl	RIa	N	Compounds ($n = 60$)	RIl	RIa
1	1-Propene^{A,B,C,D,E}	290	<500	41	Phenol^{A,B,C,D,E}	1002	998
2	Methyl chloride^{A,B,C,D,E}	325	<500	42	Benzofuran^{A,B,C,D}	1005	1002
3	2-Methylpropene^{A,B,C,D,E}	388	<500	43	1,2,3-Trimethylbenzene^{A,B,C,D,E}	–	1007
4	1-Pentene^{A,B,C,D,E}	487	<500	44	*p*-Cymene^{E}	1015	1010
5	Furan^{A,B,C,D,E}	500	<500	45	4-Hydroxybenzaldehyde^{A,B,C,D}	–	1013
6	Acetone^{A,B,C,D}	530	515	46	Limonene^{D,E}	1021	1020
7	2-Methylpropanal^{A,B,C,D}	540	518	47	*Trimethylbenzene^{A,B,C,D}	–	1025
8	3-Buten-2-one^{A,B,C,D}	561	535	48	1H-Indene^{A,B,C,D,E}	1071	1031
9	2-Methylpentane^{A,B,C,D}	562	540	49	*Trimethylbenzene^{A,B,C}	–	1037
10	2,3-Butanedione^{A,B,C,D}	575	565	50	*o*-Cresol^{A,B,C,D,E}	1048	1044
11	Hexane^{A,B,C,D}	600	600	51	*p*-Cresol^{A,B,C,D,E}	1051	1055
12	3-Methyl-butanal^{A,B,C,D}	630	615	52	*m*-Cresol^{A,B,C,D,E}	1048	1064
13	Benzene^{A,B,C,D,E}	651	644	53	2-Methoxyphenol^{A,B,C,D,E}	1074	1067
14	Acetic acid^{A,B,C,D,E}	674	651	54	α-Terpinolene^{E}	1080	1078
15	1-Heptene^{A,B,C,D,E}	689	685	55	Nonanal^{A,B,C,D,E}	1087	1083
16	2,5-Dimethylfuran^{A,C,D}	697	690	56	Undecene^{A,B,C,D,E}	1088	1086
17	Heptane^{A,B,C,D,E}	700	700	57	Undecane^{A,B,C,D,E}	1100	1100
18	1-Methylpyrrole^{A,B,D,E}	715	711	58	1-Methyl-1H-indene^{A,B,C,D,E}	1148	1130
19	Pyrrole^{A,B,C,D,E}	768	721	59	Naphtalene^{A,B,C,D,E}	1185	1161
20	Toluene^{A,B,C,D,E}	756	749	60	4-Methyl-2-methoxy-phenol^{A,B,C,D,E}	1190	1178
21	Cyclopentanone^{A,B,E}	775	758	61	Decanal^{A,B,C,D,E}	1188	1185
22	1-Octene^{A,D,E}	797	764	62	Dodecane^{A,B,C,D,E}	1200	1200
23	Octane^{A,B,C,D,E}	800	800	63	4-Hydroxystyrene^{A,B,C}	1215	1205
24	Furfural^{A,B,C,D,E}	815	836	64	Linalylacetate^{E}	1239	1240
25	Ethylbenzene^{A,B,C,D,E}	854	845	65	1,2-Benzenediole^{A,B,C}	–	1205
26	(*m* + *p*)-Xylene^{A,B,C,D,E}	860	853	66	2,3-Dihydro-1H-inden-1-one^{A,B,C,D,E}	1292	1275
27	Cyclohexanone^{B,C,E}	875	870	67	2-Methylnaphthalene^{A,B,C,D,E}	–	1276
28	Styrene^{A,B,C,D,E}	880	873	68	4-Ethyl-2-methoxyphenol^{A,B,C,D,E}	1270	1280
29	*o*-Xylene^{A,B,C,D,E}	884	880	69	Vinyl guaiacol^{A,C}	–	1284
30	1-Nonene^{A,B,C,D,E}	886	883	70	1-Methylnaphthalene^{A,B,C,D,E}	1276	1291
31	Nonane^{A,B,C,D,E}	900	900	71	2-Methoxy-4-vinylphenol^{A,B,C,D,E}	1306	1301
32	Benzaldehyde^{A,B,C,D}	947	929	72	2,6-Dimethoxyphenol^{A,B,C,D,E}	1349	1319
33	α-Pinene^{A,B,C,D,E}	942	931	73	Eugenol^{C,E}	1351	1337
34	5-Methyl-2-furancarboxaldehyde^{A,B,C,D}	944	940	74	Biphenyl^{A,B}	1366	1359
35	Propylbenzene^{A,B,C,D}	949	944	75	Longifolene^{E}	1411	1413
36	*Ethyltoluene^{A,B,C,D,E}	–	952	76	*trans*-β-Caryophylene^{E}	1421	1424
37	Benzonitrile^{A,B,C,D,E}	965	962	77	β-Copaene^{E}	1430	1431
38	*Ethyltoluene^{A}	–	971	78	Germacrene^{D,E}	1480	1480
39	3-Methylstyrene^{A,B,C,D}	988	984	79	δ-Cadinene^{E}	1524	1515
40	Decene^{A,B,C,D}	991	987				

Table 3. Concentrations of BTEXs (benzene, toluene, ethylbenzene and xylenes; mg m^{-3} ± standard deviation) identified at all sites in prescribed burning (in 15 min during the prescribed burning) and exposure limit value (ELV) and short-term exposure limit (STEL) values Data marked with a superscript letter (e.g. A, B, C, D, E) are significantly different among stations: ANOVA $P < 0.05$

Compounds	Site A ($n = 12$)	Site B ($n = 12$)	Site C ($n = 12$)	Site D ($n = 12$)	Site E ($n = 12$)	ELV	STEL
Benzene	$30^{A} \pm 2.6$	$27^{A} \pm 2.9$	$54^{B} \pm 3.0$	$40^{C} \pm 4.3$	$12^{D} \pm 1.8$	30	16
Toluene	$6^{A} \pm 0.9$	$13^{B} \pm 2.1$	$78^{C} \pm 6.1$	$15^{B} \pm 3.1$	$6^{A} \pm 0.9$	550	574
Ethylbenzene	$5^{A} \pm 0.8$	$23^{B} \pm 1.9$	$62^{C} \pm 6.9$	$23^{B} \pm 2.8$	$2^{D} \pm 0.3$	650	662
Xylene	$8^{A} \pm 0.8$	$26^{B} \pm 1.8$	$54^{C} \pm 3.1$	$32^{D} \pm 2.8$	$1^{E} \pm 0.5$	650	541
Total BTEX	$49^{A} \pm 5.1$	$89^{B} \pm 8.7$	$224^{C} \pm 28.0$	$110^{D} \pm 12.0$	$21^{E} \pm 3.5$		

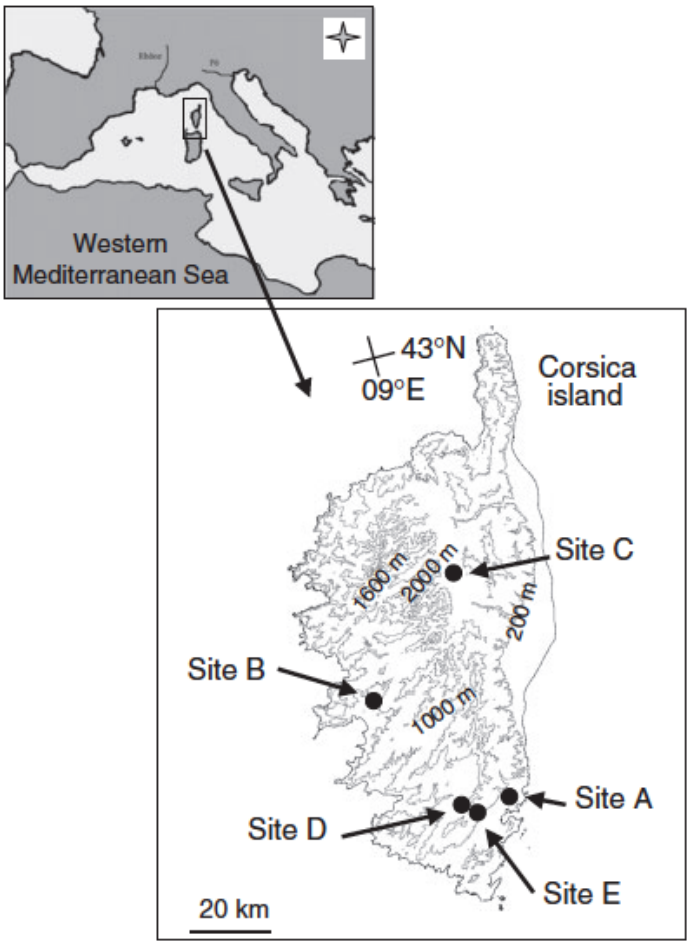

Fig. 1. Location of the study sites on Corsica (French) island.